REDUCING HARMONIC VOLTAGE AT INDUSTRIAL AREA DISTRIBUTION NETWORK USING NETWORK CONFIGURATION MANAGEMENT

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by

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LIST OF ABBREVIATION

ASD	Adjustable speed drives
BK	Breaker
Cpf	Cumulative probability function
CIGRE	International Congress of Large Power Systems
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEEE PES	IEEE Power Engineering Society
I_{SC}	Short Circuit Current
I_L	Load Current
LPC	Large Power Consumer
MS	Microsoft
MVA	Mega Volt Ampere
NOP	Normally open position
Pdf	Probability density function
PCC	Point of Common Coupling
SCC	Short Circuit Current
SCR	Short Circuit Ratio
SHI	Shunt Harmonic Impedance
THD	Total Harmonic Distortion
THD_v	Voltage Total Harmonic Distortion

MENGURANGKAN VOLTAN HARMONIK DI RANGKAIAN PEMBAHAGIAN KAWASAN INDUSTRI MENGGUNAKAN PENGURUSAN KONFIGURASI RANGKAIAN

ABSTRAK

Syarikat pembekal elektrik diperlukan untuk mengekalkan tahap voltan harmonik di dalam sistem di bawah batas piawaian. Namun, voltan harmonik berubah mengikut masa dan disebabkan oleh naik turun tahap arus harmonik dan perubahan impedans rangkaian. Mengurangkan harmonik menggunakan kaedah sedia ada adalah mahal untuk pembekal tenaga dan memerlukan pertimbangan ekonomi. Pemerhatian dan analisa ke atas rangkaian pembahagian kawasan industri menunjukkan perubahan pada impedans rangkaian disebabkan oleh perubahan beban pelanggan dan perubahan konfigurasi rangkaian boleh menyebabkan perubahan ketara terhadap kadar voltan ‘total harmonic distortion’ (THD) pada ‘point of common coupling’ (PCC). Simulasi terhadap rangkaian pembahagian ujian, menganalisa faktor seperti saiz perubahan beban pelanggan dan lokasi beban sepanjang rangkaian, dapat mengurangkan perubahan maksima voltan THD sebanyak 21.7% dari satu pelanggan. Mengubah konfigurasi rangkaian dapat mengurangkan voltan THD sebanyak 10.6% sementara menambah 5MVA beban tambahan mengurangkan voltan THD sebanyak 3.5%. Jumlah pengurangan adalah bermakna memandangkan caranya yang mudah dengan kos yang minima menjadikannya sesuai untuk pembekal tenaga atau pelanggan gunakan sebagai cara tambahan menghalang voltan harmonik daripada melebihi had piawaian atau memperbaiki bentuk gelombang voltan.

REDUCING HARMONIC VOLTAGE AT INDUSTRIAL AREA DISTRIBUTION NETWORK USING NETWORK CONFIGURATION MANAGEMENT

ABSTRACT

Electric utility company is required to maintain harmonic voltage level in the system below the standard’s limit. However, harmonic voltage is time variant and is caused by fluctuation of current harmonic level and changes in network impedance. Mitigating harmonic using existing methods is costly for utility and requires economic consideration. Observation and analysis on an industrial area distribution network shows that network impedance fluctuation caused by consumer loads variability and changing network configuration can significantly change voltage total harmonic distortion (THD) level at point of common coupling (PCC). Simulation on a test distribution network, analyzing factors such as size of fluctuating consumer load and location of load along radial network, is able to reduce maximum voltage THD variability from a single load up to 21.7%. Changing network configuration can achieve voltage THD reduction up to 10.6% while adding 5MVA additional load into the network reduced voltage THD up to 3.5%. Amount of reduction is significant considering the method’s simplicity and with minimum cost which makes it feasible for utility or consumer to use as an additional method to prevent harmonic voltage from exceeding the standard’s limit or to improve voltage waveform.

CHAPTER ONE

INTRODUCTION

Demand for quality power supply is becoming a major issue for consumer, especially large power consumer (LPC) such as industrial community. Electric utility company is expected to comply with power quality standards. One of power quality index is related to harmonic distortion. Unlike other power quality indexes such as transient, sag and swell which occur intermittently, harmonic distortion exist continuously in electrical network. This chapter describes issues regarding harmonic distortion at an industrial area distribution network from utility's perspective.

1.1 Overview on Harmonic

Harmonics in electrical power system is becoming a major concern for electric utility company and consumers. It is produced by power electronics and other equipments which are called non-linear loads. Examples of nonlinear loads are computers, fluorescent lamp and television in residential while variable speed drives, inverters and arc furnaces are mostly common in industrial areas. Increasing numbers of these loads in electrical system for the purpose of, such as improving energy efficiency, has caused an increase in harmonics pollution. These loads draw non-sinusoidal current from the system. The waveform is normally periodic according to supply frequency which is either 50Hz or 60Hz depending on the country.

Effect of high level of voltage or current harmonics can cause transformer heating, nuisance tripping of fuse, circuit breaker and protective devices, high current in neutral conductor and distorted voltage waveform. Capacitors are sensitive to harmonic voltage while transformers are sensitive to current harmonics. There are many researches which study the effect of harmonics which affects both utility and consumers. Greater concerns have been expressed by industries which have equipment or processes that are sensitive to distortion on the supply voltage which affect their plant operation and productivity.

Resonance is another problem related to harmonics. It occurs when harmonic current produced by non-linear load interacts with system impedance to produce high harmonic voltage. Two types of resonance can occur in the system, either series resonance or parallel resonance, depending on the structure of the network. This problem is most common in industrial plant due to the interaction of series of power factor correction capacitors and transformer's inductance.

All triplen harmonics (odd multiples of three i.e. 3, 9, 15 …) is zero sequence and cannot flow in a balanced three-wire systems or loads. Therefore, the delta-wye-grounded transformer at the entrance of industrial plant can block the triplen harmonic from entering utility distribution system. However, triplen harmonic current flows in neutral conductor and are three times in magnitude.

1.2 Standards on Harmonic

Institute of Electrical and Electronics Engineers (IEEE) has come out with standards and guidelines regarding harmonics. One of the standards, IEEE Standard 519-1992, provides comprehensive recommended guidelines on investigation, assessment and measurement of harmonics in power system. The standard includes steady state limits on current harmonic and harmonic voltages at all system voltage levels. The limit was set for a steady state operation and for worst case scenario.

Another international standards and conformity assessment body, International Electrotechnical Commission (IEC), produced a standard, IEC 61000-3-6, which also provides guidelines to address harmonics issue with sets of steady state limits. Both standards are in common where the limits were derived based on a basic principle of insuring voltage quality and shared responsibility between utility and customer (Halpin, 2005). Both lay the responsibility on consumer to limit the penetration of current harmonic into power system while utility company is responsible to limit harmonic voltage at point of common coupling (PCC). According to IEEE definition, point of common coupling is a point anywhere in the entire system where utility and consumer can have access for direct measurement and the indices is meaningful to both.

Example of steady state harmonic voltage limit from IEEE Std. 519-1992 at PCC for medium voltage level (< 69 kV) is 5% THD and 3% individual voltage distortion. In reality, harmonic is time-variant and it changes over time due to several factors. Both standards recognize this condition and allow the limits to be exceeded for short duration. IEC has provided a set of time-varying limits based on percentile over a period of time i.e. 95^{th} and 99^{th} for very short time (3 second) and short time (10 minute) aggregate measurements.

1.3 Harmonic Mitigation

Several methods of mitigating harmonics have been developed over the years. The most common method is using filter, either passive or active. Passive filter block certain harmonic bandwidth while active filter injects current into the system to cancel the current harmonic waveforms. Both methods have their advantages and disadvantages, for example, advantage of passive filter is easy to design and active filter can monitor many frequencies simultaneously while disadvantage of passive filter is bulky in size and active filter is costly (Izhar et. al., 2003). Harmonic filters are useful and practical to be implemented by consumer near the proximity of the non-linear load at the low voltage system. Another method which is normally used by consumers is using phase cancellation method using twelve pulse converters instead of six pulse converters.

Similar application using filters for utility at higher voltage level such as distribution network requires extensive economic consideration. This is due to the size and cost of the equipment while most of harmonic pollutant is caused by consumer. There is little study on a feasible and cost effective means for utility to mitigate harmonic, especially harmonic voltage. A study was conducted on method using shunt harmonic impedance (Ryckaert et. al., 2004) which can act like a central damper to reduce harmonic at distribution network. This method is considered to be less expensive compared to active filter. The method uses power electronic to emulate resistive behavior for harmonic. However, the method is still under further study. Currently, all harmonic mitigation techniques involve equipment required to be installed on the system. There is yet a study on using other factors which can affects harmonic voltage distortion such as network impedance. Optimizing network impedance to mitigate harmonic can be cost effective for utility to apply. Because of mitigating harmonic is expensive, many utility company have resorted in imposing penalty to consumer for injecting current harmonic above the standard steady state limit into the system. This process requires method on determining harmonic contribution by the consumers (Li, et. al., 2004) and the equipment need to be installed at all consumers' feeder which is very costly.

1.4 Time-Varying Harmonic

Many recent studies on harmonic limit focus on development of time varying limit and probabilistic aspects of harmonics in power system (Baghzouz, 2005). This includes the probabilistic modeling of power system (Carbone, et. al., 2000) and probabilistic aspects of harmonic impedance (Testa, et. al., 2002). In order to comply with time varying harmonic limits, prediction of the system's time varying harmonic characteristic is crucial. Simulation is still the best method of assessment but calculation based on steady state design value does not reflect the actual fluctuation of harmonic. This is due to the fact that current harmonic and network impedance changes over time. Therefore it is imperative for utility to be able to predict the time varying characteristic of harmonic voltage of a distribution network at PCC based on the varying factors within distribution system, especially factor that within its influence where they can be controlled or managed. The factors which can contribute to harmonic voltage fluctuation will be discussed in detail in section 1.6.

1.5 Industrial Area

Setting up of an industrial area or industrial zone has become a common practice in many countries where all industrial plant is located within a certain geographical area. There are many reasons for the set up such as economic consideration, safety issues and environmental concern. The development of industrial area has also caused a unique electrical distribution system with unique electrical characteristic, power quality and system stability requirements. Due to the strict requirements from consumer to utility, consumers are provided with redundant incoming feeders and the distribution network is supplied by several sources from transmission system. The network is also operated by extensive network control system to provide stable and reliable supply to consumers.

Utility monitors power supply quality of an industrial area at the incoming feeder after the step down transformer from transmission system. For harmonic monitoring, this point is the point of common coupling. The reason for choosing the point is to ensure harmonic pollution from the industrial area is not being transmitted into transmission system and vice versa, and to ensure harmonic pollution from one branch does not affect another branches connected on the feeder. Harmonic level on the feeder is the best indication of harmonic quality in the network.

1.6 Factors Contributing to Harmonic Fluctuation

Analysis into factors contributing to harmonic voltage fluctuation at industrial area shows that changes in non-linear loads, network configuration and number of linear loads within the network are the main factors. However, utility has no control over the number and operational of non-linear load within industrial plant which caused changes in production of current harmonic. The only factors within utility's control are configuration of the network and number of consumer plants in the network. These two factors affect the network impedance. Looking in detail into network components, network total impedance comprises of transmission system impedance, step down transformer impedance, cable impedance and consumer's plant network impedance.

Transmission system network impedance looking from the low voltage side of a step down transformer varies slightly over time because of the impedance of a step down transformer dominates and does not vary much. Cable's impedance is also constant and can be assume steady. However, number of consumer plant in the network and their load demand changes over time depending on plant operation and unforeseen tripping. Overall network configuration can also change due to switching process. These two factors, consumer load variability and network configuration changes, are the main factors which utility can use to mitigate harmonic voltage.

1.7 Evaluating Harmonic Characteristic

In order to determine the effect of the above factors on harmonic voltage, network harmonic characteristic is important as a baseline for comparison. The characteristic must be able to indicate the effect of time varying nature of harmonic. Since major contribution of harmonic voltage is the fluctuation of load impedance under normal operation, development of harmonic characteristic of a network due to load variability is crucial. There is currently no specific method been developed to determine or predicting harmonic characteristic of a certain network, other than frequency scan for resonance analysis which only applicable for steady state analysis. For this study, since utility is able to determine the statistical loading pattern of a network, the probability of loading can be used to develop and estimate the probabilistic aspect of harmonic.

1.8 Objectives and Scope of Research

The objectives of this study were to determine methods for utility to reduce harmonic voltage in meeting standard's steady state limit of 5% voltage THD and time varying limit of 95th percentile voltage THD within steady state limit at PCC. The second objective is to determine methods of reducing harmonic voltage with little or no cost. The study focused on distribution network for industrial area which has the capability of switching into other configuration since the network normally has different possible sources, backup and redundant feeders to ensure reliability of the supply system. Action plan for this study were as follows:

1. To determine whether varying consumer load increases harmonic voltage.

2. To determine amount of changes in harmonic voltage due to size of varying consumer load.
3. To determine amount of change in harmonic voltage due to location of varying consumer load.
4. To determine changes in harmonic voltage due to switching network configuration.
5. To determine changes in harmonic voltage due to adding consumer load into existing network.

1.9 Methodology

In order to achieve the objectives, the following protocol had been set up.

- Select and gather data on industrial area distribution network configuration and components
- Decide method on modeling of equipment for harmonic analysis and method of simulation
- Model the selected industrial area distribution network
- Simulate identified factors affecting harmonic voltage
- Analyze data using statistical technique and compare with calculation based on design values
- Conclude the research, suggest and recommend mitigating action

Base on protocol and action plan a flow diagram of research methodology was drawn and shown in Figure 1.1.

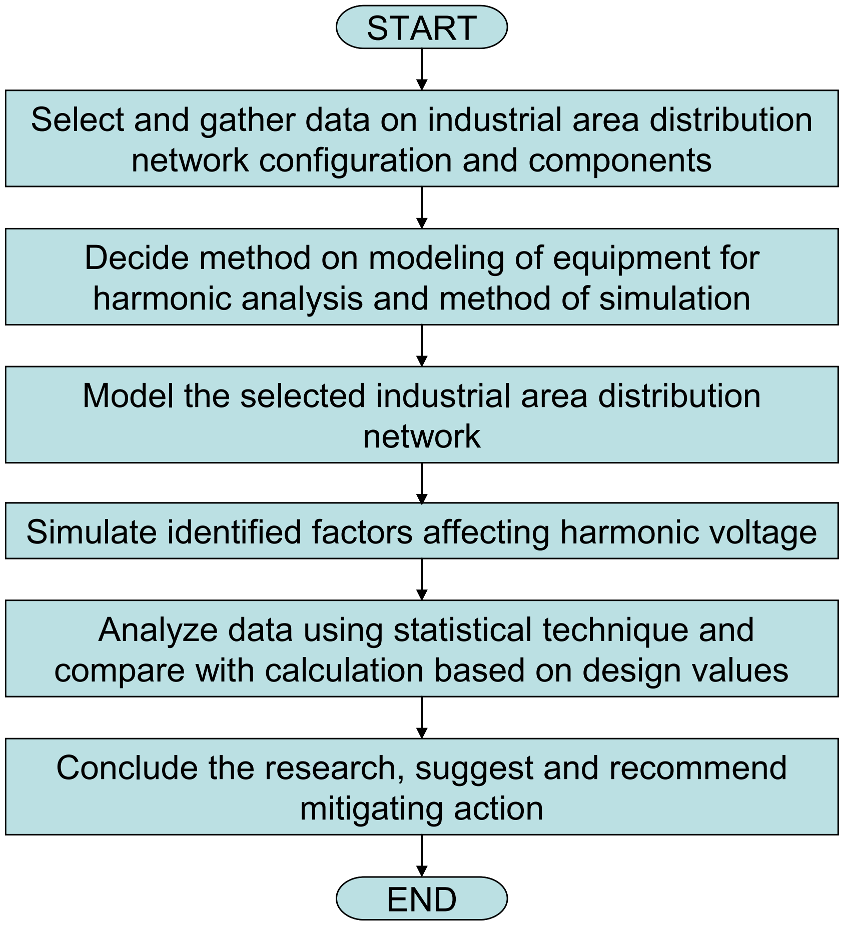

Figure 1.1 Methodology flow chart

1.10 Contribution of This Study

The outcome of this study is important to utility in controlling harmonic voltage and improving power quality without huge investment in mitigating equipment. Components which are affected by harmonic voltage will have longer life and cost of maintenance is reduced. Consumers will also benefit from the method since utility is able to provide better power quality. System design engineers can use the method in planning of electrical system and control engineers will be able to use the method in controlling harmonic voltage.

1.11 Overview of Thesis

This thesis discusses and analyzes harmonic voltage distortion at a utility distribution network supplying to industries due to changes in consumer load and network configuration. The analysis determines the condition which can reduce total harmonic voltage distortion THD_v at point of common coupling. Recommendation to reduce harmonic voltage distortion was proposed which can be integrated into the network control system.

The content in Chapter 2 provides reader with the applicable standards for harmonic, harmonic mitigation, probabilistic aspects of harmonic, economic consideration and effect of network impedance on harmonic. Reviews from past studies by researchers related to those issues were presented.

Chapter 3 discusses the method of simulation and the process flow of the simulation. Each factors contributing to the changes to harmonic voltage at PCC were taken into consideration for simulation. Method of calculations and analysis were also presented in this chapter.

Chapter 4 contains information on test distribution network system together with component data and test values that were used for analysis. Methods for modeling and calculation of each component in the network were described in details.

Chapter 5 exhibits the simulation results and analysis together with discussion of the overall situation. A conclusion of the thesis was presented in Chapter 6 which includes recommendation for future studies.

CHAPTER TWO

LITERATURE SURVEY

2.1 Background

The studies required broad knowledge of the issues regarding harmonic in power system, the standard limit and requirements, modeling and simulation, issues related to utility and consumers especially at an industrial area, and result from studies by other researchers. All this information is necessary to address the changes and dynamic of harmonic voltage at an industrial area.

The following sections include brief knowledge of harmonics and reviews on papers related to relevant harmonic standards and requirements, mitigation, probabilistic aspects, cost of mitigation and effect of harmonic impedance variability. The review focus on studies related to harmonic in power system with regards to relation between utility and consumers. The reviews also pointed out the differences and similarities between previous studies and this research.

2.2 Basic on Harmonics

IEEE PES Winter Meeting 1998 provides basic harmonic theory which according to Fourier theorem, periodic non-sinusoidal or complex voltage (Figure 2.1) or current waveforms can be represented by the sum of a series of multiple frequency terms of varying magnitudes and phases as shown in equation (2.1).

$$f(t) = a_0 + \sum [a_n \cos(n\omega t + q_n)] \qquad (2.1)$$

where: a_n is the magnitude of the nth harmonic frequency

a_o is the d.c. component

q_n is the phase angle of the nth harmonic frequency

ω is the fundamental frequency

n =1,2,3,…

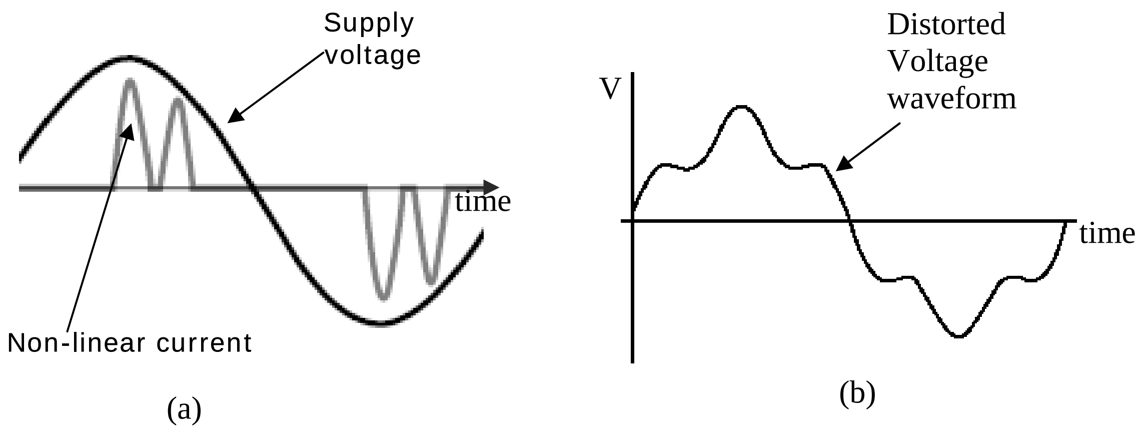

Figure 2.1 Harmonic Current and Voltage Distortion
a) Non-linear load draws non-sinusoidal current from the system.
b) Resulting voltage distortion due to non-sinusoidal current

Harmonic is measured using total harmonic distortion (THD) which is also known as distortion factor and can be applied to current and voltage. It is a square-root of sum of all harmonic magnitudes over the fundamental. Equation (2.2) shows the calculation for voltage total harmonic distortion (THD_v).

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \tag{2.2}$$

where: V_1 is the magnitude of fundamental frequency voltage

V_n is the magnitude of n^th harmonic frequency voltage

For a balanced three-phase network with three-phase non-linear loads, harmonic current or voltage has phase sequences. Equations (2.3) until (2.7) describe the equation for each phase for the first three harmonics.

$$i_a(t) = I_1 \sin(\omega_o t + \theta_1) + I_2 \sin(2\omega_o t + \theta_2) + I_3 \sin(3\omega_o t + \theta_3) \tag{2.3}$$

$$i_b(t) = I_1 \sin(\omega_o t + \theta_1 - \frac{2\pi}{3}) + I_2 \sin(2\omega_o t + \theta_2 - \frac{4\pi}{3}) + I_3 \sin(3\omega_o t + \theta_3 - \frac{6\pi}{3}) \tag{2.4}$$

$$i_c(t) = I_1 \sin(\omega_o t + \theta_1 + \frac{2\pi}{3}) + I_2 \sin(2\omega_o t + \theta_2 + \frac{4\pi}{3}) + I_3 \sin(3\omega_o t + \theta_3 + \frac{6\pi}{3}) \tag{2.5}$$

where: I_n is the nth current harmonic magnitude

ω_o is the fundamental frequency

θ_n is the nth harmonic phase angle

n = 1,2,3

Equation (2.4) and (2.5) can also be described as follows:

$$i_b(t) = I_1 \sin(\omega_o t + \theta_1 - \frac{2\pi}{3}) + I_2 \sin(2\omega_o t + \theta_2 + \frac{2\pi}{3}) + I_3 \sin(3\omega_o t + \theta_3 - 0) \qquad (2.6)$$

$$i_c(t) = I_1 \sin(\omega_o t + \theta_1 + \frac{2\pi}{3}) + I_2 \sin(2\omega_o t + \theta_2 - \frac{2\pi}{3}) + I_3 \sin(3\omega_o t + \theta_3 + 0) \qquad (2.7)$$

Current magnitude of all phases for all harmonic frequencies is equal for a balanced system. Looking at equations (2.3), (2.6) and (2.7), the first harmonic or the fundamental is positive sequence since $i_b(t)$ lags $i_a(t)$ by 120^o and $i_c(t)$ leads $i_a(t)$ by 120^o. The second harmonic is negative sequence since and $i_b(t)$ leads $i_a(t)$ by 120^o and $i_c(t)$ lags $i_a(t)$ by 120^o. The third harmonic is zero sequence since $i_b(t)$ and $i_c(t)$ are in phase with $i_a(t)$. The sequence pattern for each harmonic order is shown in Table 2.1.

Table 2.1
Harmonic Phase Sequence

Harmonic	Phase Sequence
1	+
2	-
3	0
4	+
5	-
6	0
7	+
8	-
9	0
10	+
11	-
12	0
13	+
14	-
15	0
…	…

2.3 Harmonic Characteristic of Industrial Area

IEEE 519-1992 standard describes that harmonic characteristic in an industrial plant are mostly balanced. Since most consumers inside an industrial area are industrial plant and most of the loads in industrial plant are three phase and balanced it can be assumed that the characteristic of industrial area distribution network is also balanced. This includes the non-linear loads. Figure 2.2 shows an actual example of an industrial network at Penang Island.

The proportion of three phase loads to single phase loads is large. Therefore, current harmonic produced within industrial plant and subsequently penetrated into utility distribution network is considered balanced. Investigation on harmonic characteristic on a real industrial area shows that harmonic voltage is practically balanced as shown in Figure 2.3. Since step down delta-wye grounded transformer at the entrance of industrial plant can block triplen harmonic, triplen current harmonic is almost non-existence in utility distribution network. Further observation shows that, even harmonic order is minimal as shown in Figure 2.4. It is can be assumed that harmonic characteristic of industrial area distribution network is similar to the characteristic of industrial plant.

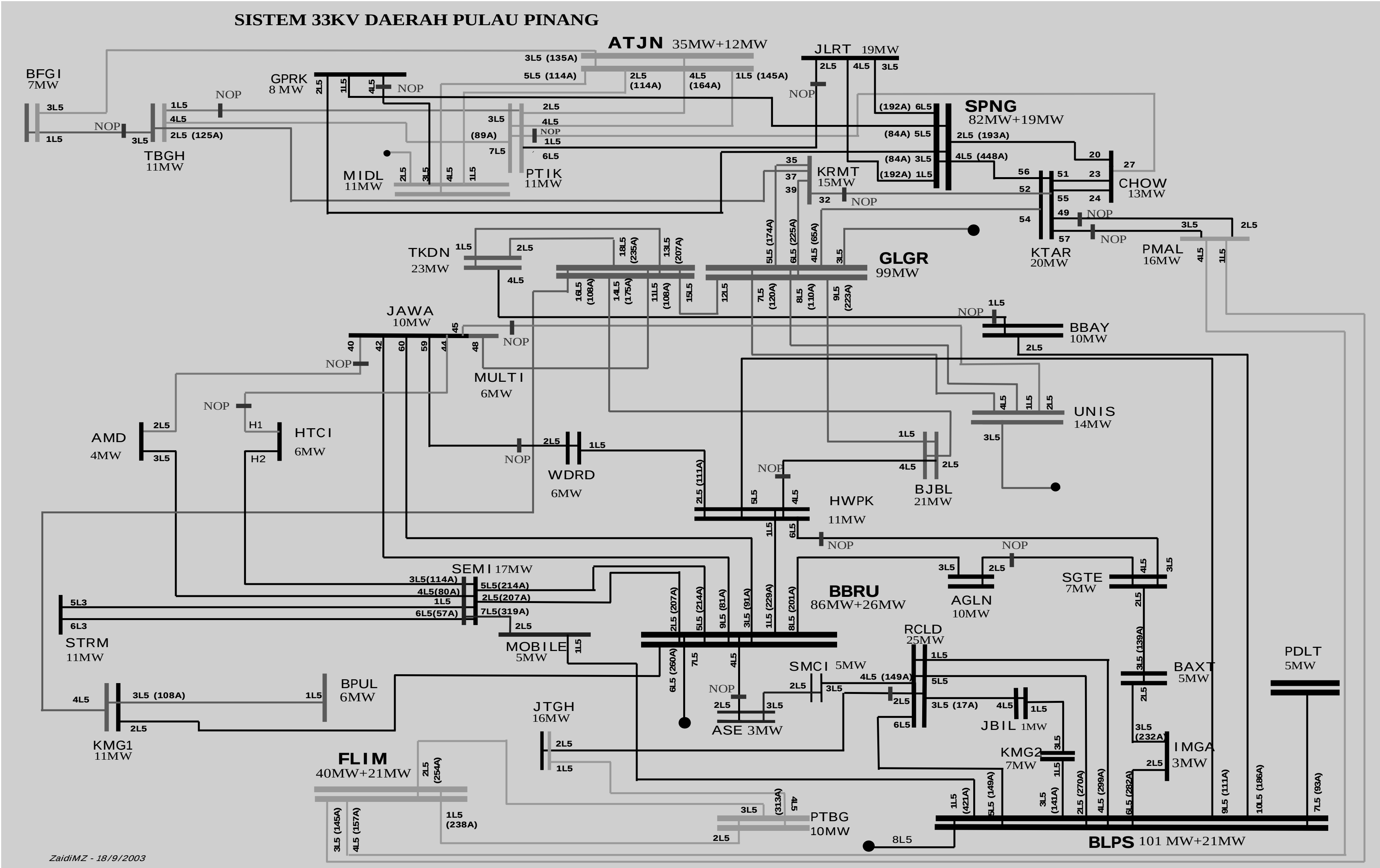

Figure 2.2 A 33KV Industrial Area Distribution Network.

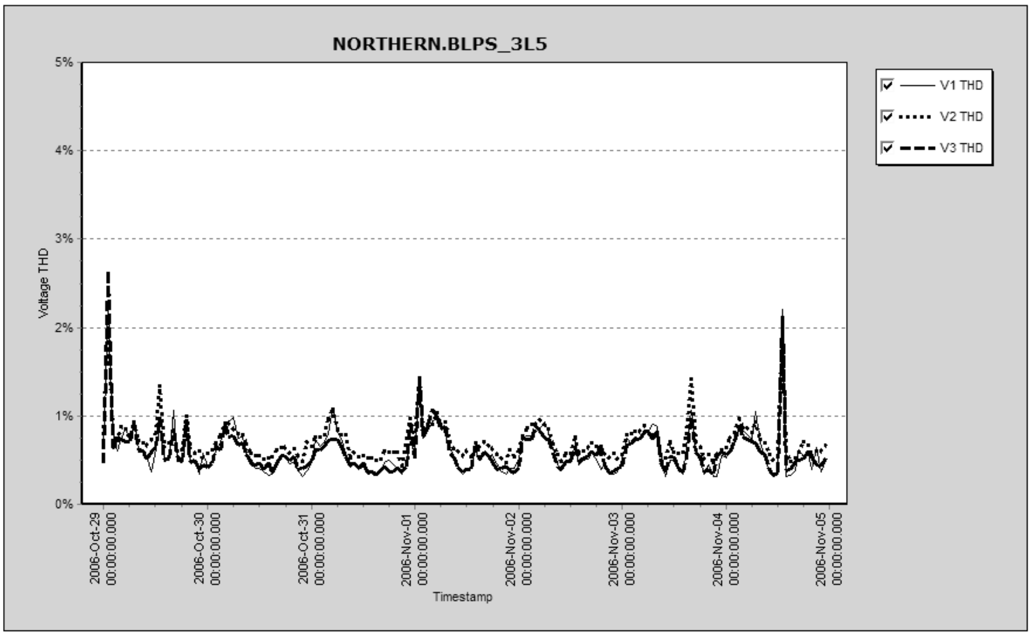

Figure 2.3 Balanced harmonic characteristic at industrial area network

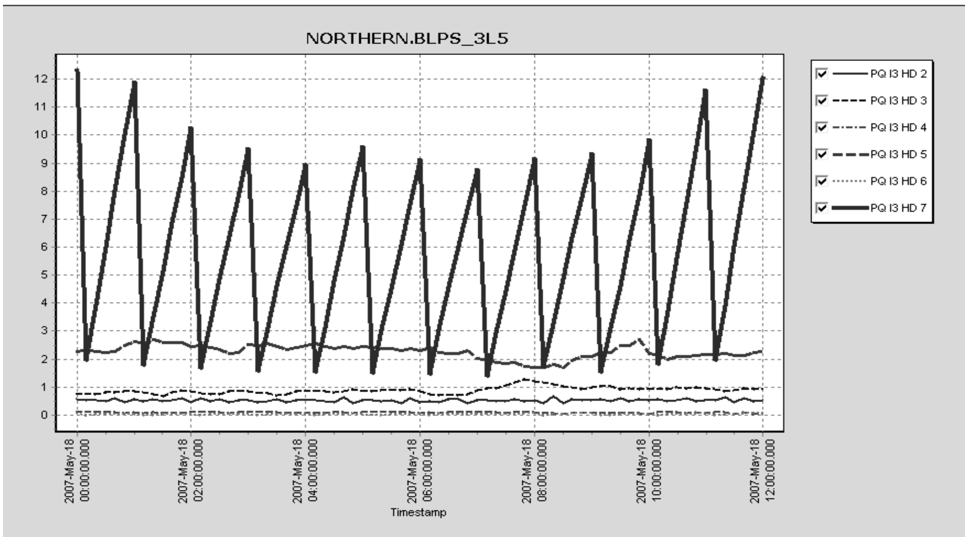

Figure 2.4 Minimal levels of triplen and even current harmonic

Figure 2.5 shows a simple industrial area distribution network with current harmonic flows from all branches and transmission system into PCC. As an example, current harmonic from transmission system I_{hT} flowing into distribution network incoming feeder and combined with network impedance creates harmonic voltage distortion at PCC. If the harmonic voltage at PCC is lower than limit, harmonic voltage down the line at consumer's feeder should be lower. Similar situation happen with current harmonic from other branches.

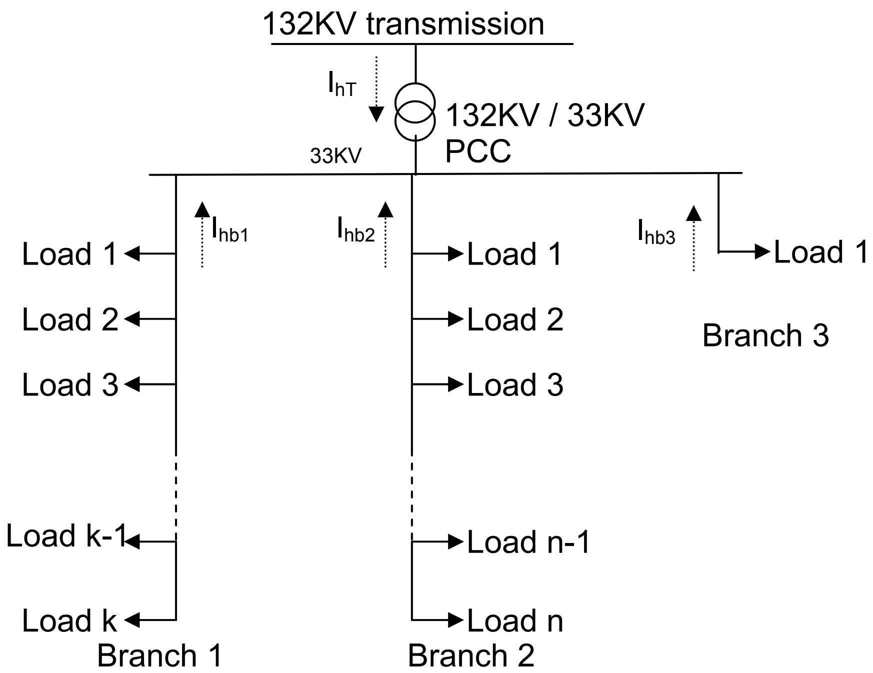

Figure 2.5 Typical distribution network of an industrial area

2.4 Harmonic Standards

IEEE has come out with a guidelines and standard regarding harmonics in the IEEE standard 519-1992 "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems". The Standard is a guide in designing of power systems with nonlinear loads. The limits set are for steady-state operation and recommended for worst case scenario. The quality of power is observed at point of common coupling (PCC) which is the interface between source and loads.

The standard generally provide information and guidelines on sources of harmonics, resonant condition due to harmonics, frequency response and modeling for transmission and distribution system, effect of harmonic, balanced and unbalanced system, measurements and steady state limits. The voltage distortion limits are used as a system design values set for worst case scenario in a normal condition. However, the worst case scenario is normally referred to maximum current harmonic penetration. Fluctuation of harmonic impedance in the system can also cause an increase in harmonic voltage. This study looks at varying factors of harmonic impedance within a distribution network and compare with harmonic voltage distortion limit at point of common coupling using design components values and maximum current harmonic penetration from a single source. Table 2.2, 2.3 and 2.4 are the harmonic current and voltage limits from IEEE 519-1992 standard.

Table 2.2
Basis for harmonic current limits based on IEEE 519-1992

SCR at PCC	Maximum individual Frequency Harmonic voltage (%)
10	2.5 – 3.0%
20	2.0 – 2.5%
50	1.0 – 1.5%
100	0.5 – 1.0%
1000	0.05 – 0.10%

Table 2.3
Current distortion limit for general distribution systems (120V through 69000V)

I_{SC}/I_L	< 11 [%]	11≤h<17 [%]	17≤h<23 [%]	23≤h<35 [%]	35≤h [%]	TDD [%]
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonic are limited to 25% of the odd harmonic limits above						

Table 2.4
Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69kV and below	3.0	5.0
69.001kV through 161kV	1.5	2.5
161.001kV and above	1.0	1.5

Another standard for harmonic is IEC 61000-3-6. A paper by Halpin (2005) provides comparisons between IEEE and IEC standards, both similarities and differences. The paper touched on areas such as driving principle, harmonic voltage limits, current harmonic limits, even-order harmonic, non-characteristic harmonic, time-varying harmonic and inter-harmonic. Both standards aim at a similar goal which is to ensure voltage quality with the main principle of shared responsibility between utility and customer. IEC provide comprehensive limits on time-varying harmonic compared to IEEE. The IEC time-varying harmonic limit is based on percentiles, e.g. 95^{th} and 99^{th} for very short time (3 second) and short time (10 minute) aggregate measurements.

This research is putting an effort to provide means to fulfill both standards main principle which is to ensure voltage quality and also takes into account time varying aspect of harmonics. Focus is given on methods for utility to mitigate harmonic voltage at PCC in an industrial area distribution network based on steady state limit and time-varying limits. Limits from both standards were taken into account. However, these standards do not provide method to assess network's harmonic time-varying aspect which takes into consideration time varying factors.

2.5 Time Varying Harmonic

Since harmonic is time variant, it is important to understand the factors affecting the change. Mitigating harmonic to meet with standard steady state limit is essential to ensure system stability. However, since harmonic is time variant, it is more practical to use time varying limit as an index to evaluate the state of harmonics in a system. Figure 2.6 shows an actual voltage total harmonic distortion (THDv) level at an industrial area distribution network incoming feeder.

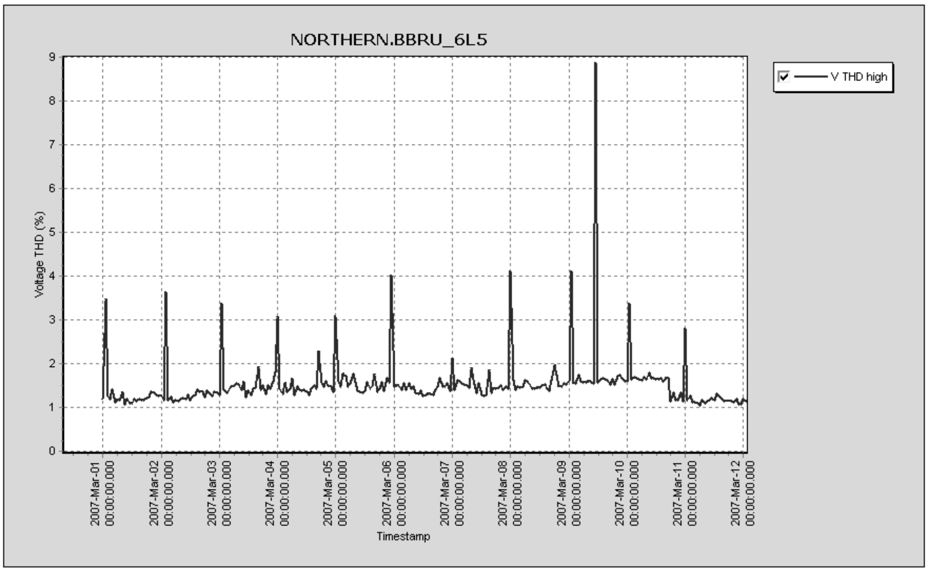

Figure 2.6 Harmonic voltage fluctuation at an industrial area incoming feeder (courtesy of Tenaga Nasional Berhad)

Baghzouz (2005) in his paper described factors contributing to the fluctuation of harmonics. Those factors are 1) changes in load condition, 2) system reconfiguration such as switching of capacitors and feeders, 3) load composition and voltage supply, 4) numbers of non-linear load in the system at any given time. The paper further discussed on the accuracy of gathered data, means of characterizing data, issues of summing harmonic phasors and statistical characteristics of harmonics resulting from multiple harmonic current injection in a network. This research focuses on the effect of changes on load condition and system configuration on network impedance which caused changes in harmonic voltage at PCC. As for fluctuation of current harmonic, a maximum value was used to determine worst case scenario. To reduce complexity of simulation and calculation, a single harmonic source is used since the purpose of this research is to determine the characteristic of load and system configuration which can reduce harmonic voltage at PCC.

Analyzing time-varying harmonic requires accurate modeling of power system. The papers by Carbone et. al. (2000) and Testa et. al (2002) studied the probabilistic modeling of an industrial system based on IEEE industrial test system. The research performed harmonic modeling as suggested by IEEE Harmonic Modeling and Simulation Task Force on supply system including generator, cables, transformers and loads. Lines and cables were modeled using R-X model excluding their capacitance due to short distance. The simulation takes into account of component parameter uncertainty, load variability, supply configuration and changes in ASD current. Harmonic voltage distortion analysis was performed using two methods, first simplified procedure using the product V=ZI to the homologous statistic parameter while the second method using Ohms Law on all determination of Z and I and utilize Bayes relation to obtain voltage probability.

Comparing this research and the paper above, both agrees on accounting system impedance and current variability and their correlation to obtain accurate harmonic voltage distortion. This research is similar in the sense of taking into account impedance variability but concentrate on different type network. The paper analyze on industrial plant distribution network which help customer in analyzing harmonic distortion, while this research analyze on industrial area distribution network which assist utility to mitigate harmonic distortion. Factors needed for consideration in modeling distribution network compare to industrial plant is the line and cable capacitance due to longer distance. Another one is the load modeling. Load in industrial plant can be easily identified as resistive, capacitive, inductive or combinations of those. Modeling is easy following IEEE recommendation. Utility is unable to determine the configuration within an industrial plant, hence, aggregate load model recommended by IEEE is required in analysis.

2.6 Harmonic Mitigation and Economic Consideration

Harmonic mitigation has been a subject of many researches. The most common mitigation technique is using filters, either passive or active. The paper by Izhar et. al. (2003) explained on harmonic theory, definitions, measurements and problems related to harmonic. It also includes harmonic reduction techniques using RLC passive filter and active power filter. The paper describes the advantages and disadvantages of both filters. Generally, active filter is the best solution compared to passive filter but is more complicated and expensive. Utilizing filters either active or passive at utility distribution network is expensive and require economic consideration. This is owed to major harmonic pollution